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TIME-DOMAIN PULSE ANALYSIS AS A SUBSTITUTE FOR ULTRASONIC SPECT--ETC(U)
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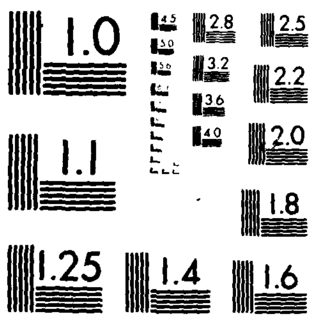

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TIME-DOMAIN PULSE ANALYSIS AS A SUBSTITUTE FOR ULTRASONIC SPECTROSCOPY.

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Final rept.

OTTO R. GERICKE
MATERIALS TESTING TECHNOLOGY DIVISION

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ABSTRACT

A computer method, based on fast Fourier transformation principles, has been used to study various types of pulsed signals and their associated spectral functions. Theoretical criteria were developed for generating a pulse that exhibits a broad, uniform spectrum while satisfying the practical requirements of the electronic instrumentation currently available for ultrasonic testing purposes.

Further investigation was made of how the time-domain appearance of such a broad-spectrum pulse is changed if the signal is subjected to various forms of frequency-dependent attenuation. The results obtained demonstrate the feasibility of establishing a systematic correlation between pulse shape and attenuation function. This leads to the conclusion that ultrasonic attenuation phenomena can be examined by means of a time-domain signal analysis in lieu of the more involved spectrum analysis.

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CONTENTS

INTRODUCTION

An earlier study[1] of pulse shapes and associated spectra aimed at establishing a formal basis for the then newly developed concept of ultrasonic pulse-echo spectroscopy had to be limited to idealized time functions to keep the required computer time to a minimum. Even with such limitations, computation times in excess of ten hours were needed to obtain a single set of data. Furthermore, in order to obtain accurate graphic representations of time-domain functions and spectra the data had to be plotted by hand.

Since that time, great strides have been made in the area of digital computing. Today, computers are not only much faster but can also provide direct, accurate plotting of data. In addition, algorithms for numerical Fourier analysis have been developed, called Fast Fourier Transforms (FFT),[2] which result in considerably shortened computation times.

In view of these improvements on the computational scene, a new study of the pulse-shape versus spectrum problem appeared promising, particularly since it became possible to investigate a larger variety of signals within a reasonable time frame. Initially, a number of basic pulse forms were examined. The study then progressed toward more complex time-domain waveforms representative of signals encountered in contemporary ultrasonic pulse-echo test systems. The main objective of the work was to determine how the shape of a broadband ultrasonic pulse is changed in the process of passing through a material exhibiting a frequency-dependent attenuation for ultrasonic energy.

UNIDIRECTIONAL PULSES

As a follow-up to the earlier effort,[1] unidirectional (or direct-current) pulses were examined. A simple, highly idealized form of such a signal is a rectangular pulse with infinitesimally short rise and decay time. The upper trace of Figure 1a portrays such a pulse which has a precisely defined duration of 0.25 microsecond. In accordance with Fourier theory, such a pulse is associated with an unlimited spectral function whose frequency components extend to infinity. Therefore, a graphic rendition can be provided only for part of the pulse spectrum, for example, the 0 to 32 MHz range shown as the lower trace of Figure 1a. The displayed spectrum is a plot of absolute amplitude versus frequency. One notes that the spectral amplitude decays towards higher frequencies and exhibits characteristic equally-spaced nulls. Figure 1b illustrates how the spectrum is changed if the pulse length is reduced to 0.125 microsecond. Observed is an overall decline in spectral amplitude and a wider (actually doubled) spacing of nulls.

These examples illustrate a basic problem encountered in ultrasonic pulse-echo spectroscopy. Although the time-domain signals considered in Figure 1 constitute the ultimate in simplicity, their spectral functions are quite complex and thus hardly ideal for an easy interpretation of spectral changes that are caused, for instance,

1. **GERICKE, O. R.** ***Determination of Defect Geometry and Material Microstructure by Ultrasonic Pulse Analysis Testing*** **in Proceedings of the Third National Symposium of Nondestructive Testing of Aircraft and Missile Components, San Antonio, Texas, 1962, p. 199-211; also Army Materials and Mechanics Research Center, WAL TR 830.5/3, January 1962.**
2. **AHMED, N., and RAO, K. R.** ***Orthogonal Transforms for Digital Signal Processing.*** **Springer-Verlag, Berlin, New York, 1975.**

by a frequency-dependent signal attenuation. A spectrum exhibiting more uniformity over the 0 to 32 MHz range can be obtained if the duration of the rectangular pulse is drastically reduced. The pros and cons of that approach will be discussed later.

In continuing the assessment of unidirectional pulses, a more realistic form of a rectangular pulse shall be discussed which has a finite rise and decay time as illustrated by the upper trace of Figure 2a. In comparison to Figure 1a, the spectrum of

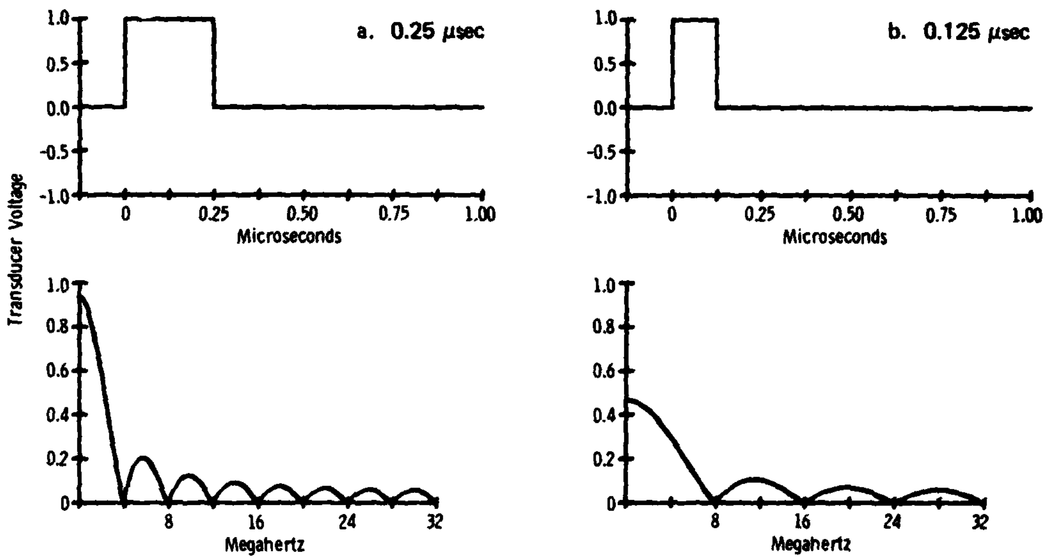

Figure 1. Rectangular pulse (upper traces) and 0 to 32 MHz portion of the spectrum associated with the pulse (lower traces).

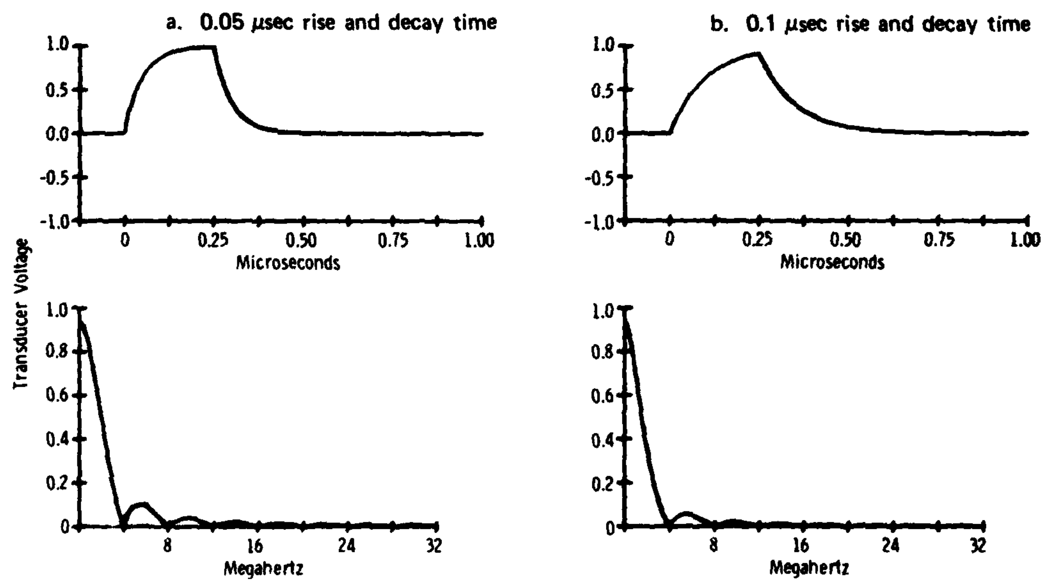

Figure 2. Pulse of 0.25 µsec duration (upper traces) and 0 to 32 MHz portion of the spectrum associated with the pulse (lower traces).

this pulse (lower trace of Figure 2a) exhibits a faster amplitude decay toward higher frequencies. An increase in the rise and decay time of the pulse results in an even more rapid drop-off in spectral amplitude toward higher frequencies, as illustrated in Figure 2b.

A further important aspect, evident from a comparison of Figures 1a and 2a and b, is the fact that the position or spacing of the spectral nulls is not affected at all by the pulse's rise and decay time. Hence it is not possible to obtain a smoother and more uniform spectrum merely by manipulating the rise and decay time of a rectangular pulse.

CARRIER-FREQUENCY PULSES

A logical next step in the search for a signal with a uniform spectrum is to look at carrier-frequency (or radio-frequency) pulses with rectangular envelopes. An example is shown by the upper trace of Figure 3 which depicts a pulse with a 4-MHz carrier. The spectrum of this pulse, again plotted in absolute amplitude values, is displayed by the lower trace. It exhibits some similarity with the spectrum of the rectangular d.c. pulse of Figure 1a.

A major difference, however, is the fact that the spectral maximum is shifted to 4 MHz. In addition, one observes an overall reduction in spectral amplitude. A further significant factor is that the largest spectral lobe of the r.f. pulse is twice as wide as that of the d.c. pulse. That characteristic is advantageous from the point of view of achieving spectral uniformity and will be a consideration in the design of a special broadband signal discussed below.

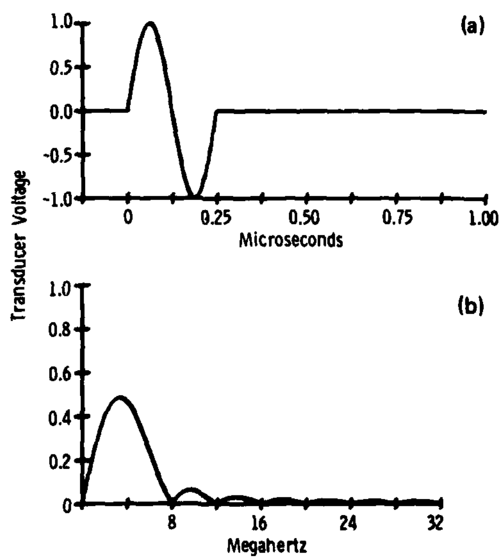

Figure 3. Four MHz radio-frequency pulse with rectangular envelope of 0.25 µsec duration (a) and 0 to 32 MHz portion of the spectrum associated with the pulse (b).

If the carrier frequency of the pulse is raised to 8 MHz, the spectral maximum is shifted to 8 MHz. In addition, a new spectral lobe appears located between 0 and 4 MHz, as is illustrated by Figure 4a. The spectral nulls, however, have the same spacing as in the previous case.

In Figure 4b, the rectangular envelope of the r.f. pulse has been doubled in length without changing its carrier frequency. This leads, as the lower trace of that figure indicates, to an increase in spectral amplitude similar to that observed in Figure 1 for d.c. pulses. In addition, doubling the pulse length causes the number of amplitude nulls per unit of frequency to double.

Comparing again the spectra of Figures 1a and 3, one notes some further interesting facts. The maximum spectral amplitude of the unidirectional pulse is twice that of the r.f. pulse. Furthermore, in the case of the d.c. pulse, spectral amplitudes diminish more slowly toward higher frequencies.

The above results are summarized in Table 1 and rated from the aspect of attaining a smooth, uniform spectrum adaptable for ultrasonic spectroscopy.

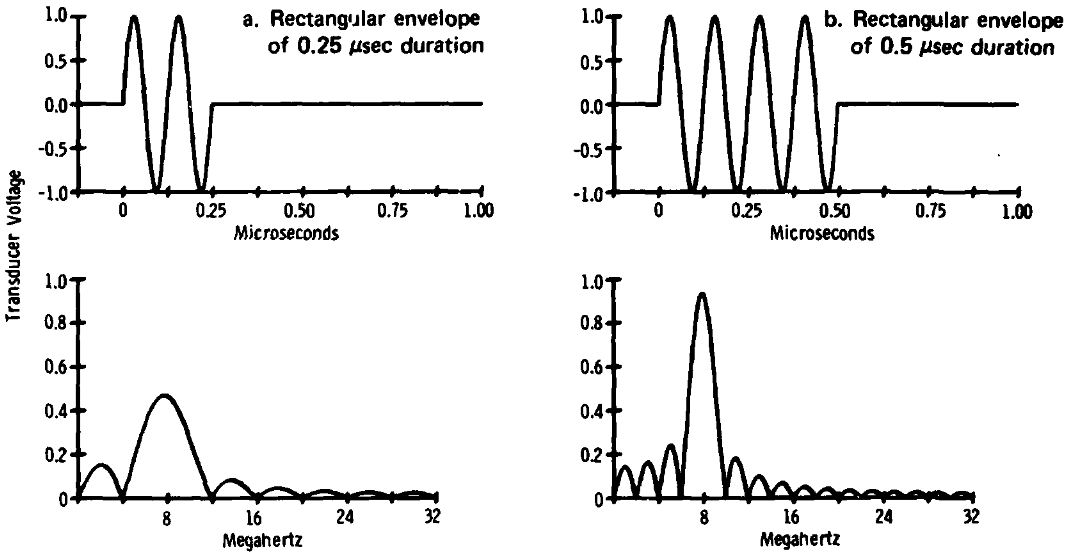

Figure 4. Eight MHz radio-frequency pulse (upper traces) and 0 to 32 MHz portion of the spectrum associated with the pulse (lower traces).

Table 1. EFFECTS OF CHANGES IN THE TIME DOMAIN OF A PULSED SIGNAL ON ITS FREQUENCY DOMAIN

Time-Domain Change	Frequency-Domain Advantage	Frequency-Domain Disadvantage
Shortened pulse	Fewer nulls	Lower amplitudes
d.c. versus r.f. pulse	Higher amplitudes, stronger upper frequency components	Narrower main lobe
Faster rise and decay	Stronger upper frequency components	

PULSES WITH UNIFORM SPECTRA

It was mentioned earlier, during the discussion of unidirectional pulses, that a really short signal of that type can provide a uniform spectrum over a certain limited range of frequencies. In pursuing this possibility further, the designation 'short' must be clarified. For that purpose, a rectangular pulse is shown in Figure 5a which has a much shorter duration than the pulses discussed earlier. The length of the pulse (upper trace) is 0.008 microsecond. Its spectrum, plotted over a much wider frequency range than those shown before, is depicted as the lower trace. One notes that within a range of 0 to 8 MHz (the 8-MHz point is marked by a dotted vertical line), spectral amplitudes are practically constant. This can be expressed numerically by stating that a rectangular pulse will exhibit a uniform spectrum up to a high-frequency limit that is equal to the inverse of the pulse's duration divided by about 16. The value, 0.008 microsecond, actually 1/128 of a microsecond, was chosen for this example to accommodate the particular computer algorithm used for the required FFT operations.

As a further example, Figure 5b shows the data for a rectangular pulse which is twice as long as the one in Figure 5a. The uniform portion of the spectrum of this pulse now extends to only 4 MHz or one half the uniform portion of the 0.008 microsecond pulse. In comparing Figures 5a and b, one notes further that the overall spectral amplitude increases in proportion to the pulse duration (compare also Figures 1a and b), provided the signals have equal amplitudes in the time domain. In other words, the excitation of an ultrasonic transducer by a rectangular pulse, which is, of course, limited in amplitude by the electric breakdown of the piezoelectric element, will involve increased signal-to-noise problems as the pulse is shortened to obtain a more uniform spectrum.

In order to overcome the limitations in spectral signal strength inherent in short pulses, a new approach was pursued. The novel concept was based on the knowledge that a piezoelectric transducer plate, when electrostatically excited, will vibrate not only

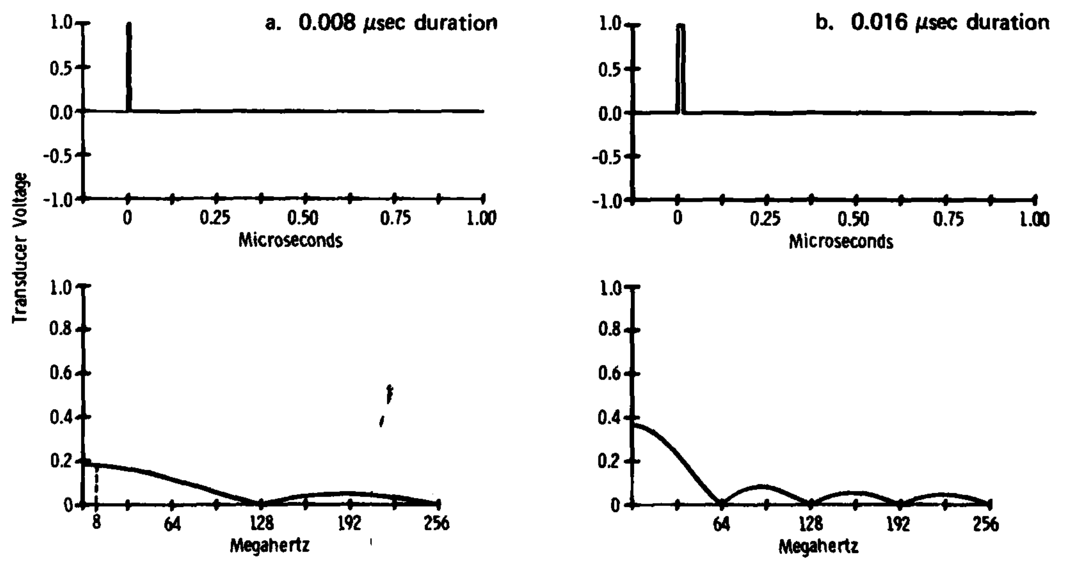

Figure 5. Rectangular pulse (upper traces) and 0 to 256 MHz portion of the spectrum associated with the pulse (lower traces). The 8 MHz spectral amplitude is indicated by a dotted line in Figure 5a.

at its fundamental thickness resonance but also at odd multiples thereof. In addition, the previously discussed spectral characteristics of radio-frequency pulses were taken into consideration in creating a special pulsed signal with a uniform spectrum.

After considerable experimentation with various combinations of r.f. pulses, which was greatly facilitated by the speed of the Fourier transform process, a suitable signal was eventually discovered. It consists of the superposition of six r.f. pulses having equal durations of 0.25 microsecond and equal rise and decay times of 0.05 and 0.1 microsecond. The carrier frequencies of these pulses are 1, 3, 5, 7, 9, and 11 MHz. At the onset of the pulse, the 1, 5, and 9 MHz carrier frequencies are 180 degrees out-of-phase with the 3, 7, and 11 MHz components. The special composite pulse is shown in Figure 6, together with its spectrum which covers a range of 0 to 10 MHz with substantially higher amplitudes than those observed in Figure 5a for the short d.c. pulse. An expanded plot of the spectrum, covering only 0 to 16 MHz, given by Figure 6a, shows good spectral uniformity over a range of 0 to 10 MHz where most of the energy of the pulse is concentrated.

In view of the fact that the frequency response of ultrasonic transducers is generally limited to 3 to 4 octaves, it seemed advisable to eliminate the frequency components below 1 MHz and above 14 MHz from the spectrum of the composite signal. That modification led to the spectrum depicted as the lower trace of Figure 7. An inverse FFT produced the time-domain function shown as the upper trace.

A comparison of Figures 6 and 7 shows that the change in pulse shape caused by the restriction in spectral bandwidth is relatively minor. The modified pulse was therefore adopted for a subsequent investigation of signal attenuation effects.

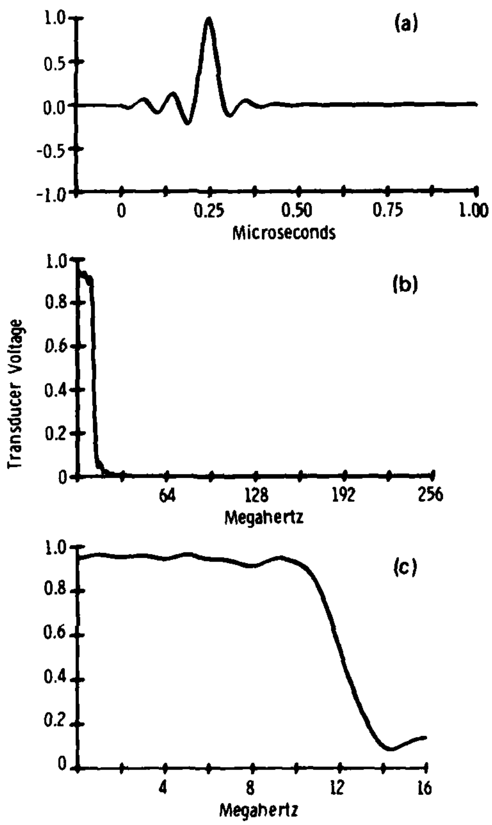

Figure 6. Special pulse (a), 0 to 256 MHz portion (b), and expansion of 0 to 16 MHz range (c) of the spectrum associated with the pulse.

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EFFECTS OF FREQUENCY-DEPENDENT SIGNAL ATTENUATION

The next step in this investigation was to determine how the signal shown in Figure 7 would be affected by frequency-dependent amplitude attenuation processes of the type that ultrasonic signals undergo in passing through various categories of engineering materials.

The first case investigated was a signal attenuation that is proportional to the frequency measured in units of megahertz. In other words, the amplitude of the 1-MHz component of the signal was considered to remain unaffected while, for example, at 5 MHz the signal amplitude was thought to be reduced to 1/5 of its original value. The effect of this type of attenuation on the pulse shape was determined by changing its spectral amplitudes in accordance with the attenuation function and then transforming the modified spectrum into the time domain. Figure 8 shows the results.

Comparison of Figure 8 with Figure 7 shows the obvious differences in the two spectral functions. The time-domain functions, however, do not seem to differ much from each other, except for a reduction in the waviness of the baseline before and after the main body of the pulse observed in the case of the attenuated signal. But, upon closer scrutiny, the time-domain functions reveal additional differences. If the attenuated and the unattenuated pulses are plotted superimposed and on an expanded time scale, it becomes evident that the main part of the pulse has been broadened by the attenuation effect. This is illustrated in Figure 9 which was obtained by individually normalizing the signal amplitudes with respect to their maximum values and plotting them on top of each other. The trace of the unattenuated signal is shown as a dotted line in this and following figures.

In order to establish a quantitative measure for the attenuation effect, the durations of the main parts of the pulses shown in Figure 9 were determined at the 0.5 amplitude level. That yielded 0.047 microsecond for the half-width of the unattenuated pulse versus 0.070 microsecond for the half-width of the attenuated pulse, a substantial difference.

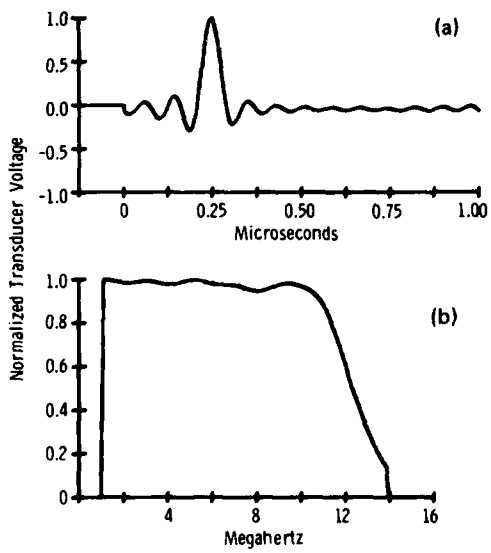

Figure 7. Special pulse (a) with spectrum limited to a 1 to 14 MHz range (b).

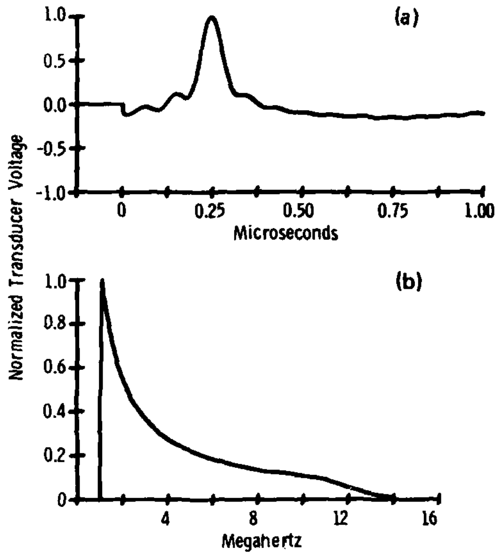

Figure 8. Special pulse of Figure 7 after attenuation proportional to the frequency in megahertz (a) and its spectrum (b).

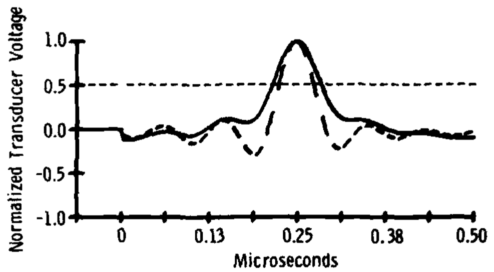

Figure 9. Expanded plot of the time domains of Figures 7 (dotted curve) and 8 superimposed.

Next, another type of frequency-dependent attenuation shall be discussed which is characterized by a decrease in spectral amplitude proportional to the square of the frequency measured in megahertz. Again, the 1-MHz component of the signal remains unchanged by the attenuation while the amplitudes of the higher frequencies decrease in proportion to $1/f^2$ (f = frequency in megahertz). The influence of this type of loss function on the pulse width is illustrated in Figure 10a which shows a superposition of the unattenuated and the attenuated time-domain signals. One notes that the half-width of the attenuated pulse is now increased to 0.125 microsecond. The spectrum associated with this attenuated pulse is depicted in Figure 10b. It shows the sharper drop-off in spectral amplitude toward higher frequencies which is characteristic for the $1/f^2$ loss function.

A third case involved a signal attenuation that decreases spectral amplitudes as $1/\sqrt{f}$. The resultant pulse spectrum is given in Figure 11 and shows the anticipated more moderate decline in spectral amplitudes toward higher frequencies. Figure 12 depicts the unattenuated and the attenuated pulses superimposed on each other and indicates that the half-width of the attenuated signal in this case is 0.055 microsecond, which is less than in the previous two examples.

All three attenuation functions were of the type that causes a reduction in spectral amplitude with increasing frequency, which is the situation normally encountered when ultrasonic energy passes through engineering materials. If the opposite is true,

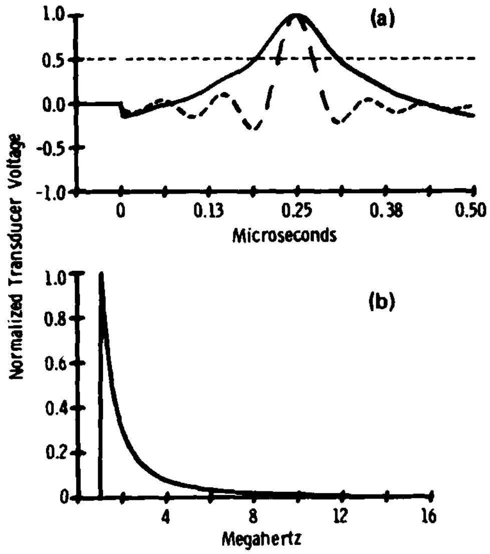

Figure 10. Expanded plot of the time domains of Figure 7 (dotted curve) superimposed on the special pulse (a) and spectrum of the special pulse (b) after attenuation proportional to the square root of the frequency in megahertz.

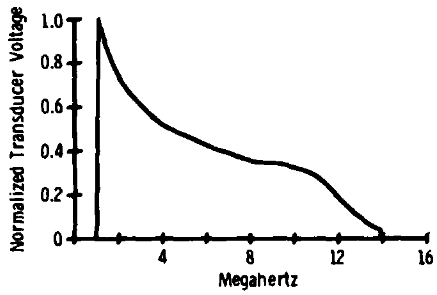

Figure 11. Spectrum of the special pulse of Figure 7 after attenuation proportional to the square root of the frequency in megahertz.

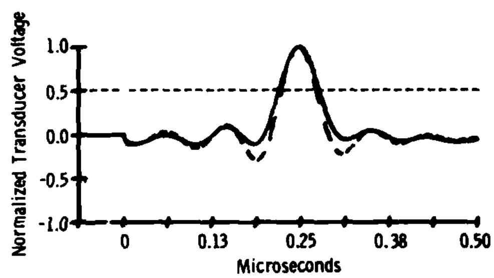

Figure 12. Superposition of the special pulse of Figure 7 (dotted curve) and the pulse obtained after attenuation proportional to the square root of the frequency in megahertz (trace with the longer duration of the larger cycle).

that is, if losses decrease with increasing spectral frequency, the effect on the pulse shape can be expected to be different. An example for that type of attenuation is shown by the spectrum of Figure 13. An attenuation function was assumed that causes amplitudes to grow in proportion to the frequency in megahertz. Again, the 1-MHz component is the reference point and remains actually unaffected by the attenuation but, due to amplitude normalization, exhibits a lower amplitude than the higher frequency components.

Figure 14 shows a superposition of the unattenuated and the attenuated time-domain signals. In contrast to the earlier cases, the half-width of the attenuated pulse is now shorter, only 0.039 microsecond, compared to the 0.047 microsecond width of the unattenuated pulse. While this type of attenuation may have little practical significance, it is important to consider it from a theoretical point of view because the pulse width continues to follow the trend established by the other examples.

The effects of the various attenuation processes on the width of the specially created broadband pulse of Figure 7 are compiled in Table 2 which shows there is a systematic relationship between the half-width of the special pulse and the attenuation function.

A closer examination of the data indicates that a mathematical expression can be developed which relates the half-width of the pulse to the exponent x in the expression for the spectral amplitude $A = A(0) \cdot f^x$, where A(0) is the spectral amplitude at 1 MHz (unattenuated), and f is frequency in megahertz.

The following equation is derived by a parabolic approximation of the data:

$$x = 1 - \sqrt{(w - 0.039)/0.008}$$

where w is the half-width of the pulse in microseconds.

In Table 3 the exponent x is shown opposite values of the half-width w obtained first by graphical evaluation of the time-domain plots and then by application of the equation. A comparison of the two sets of values for w shows a fairly good correspondence indicating that the empirically derived equation is suitable for interpolating between the values of x or w listed in Table 3.

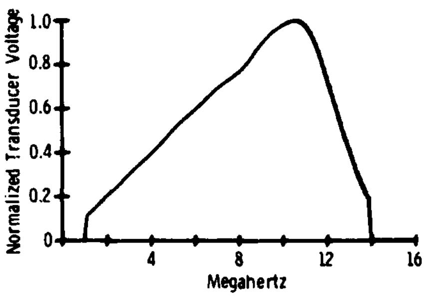

Figure 13. Spectrum of the special pulse of Figure 7 obtained after attenuation proportional to the inverse of the frequency in megahertz.

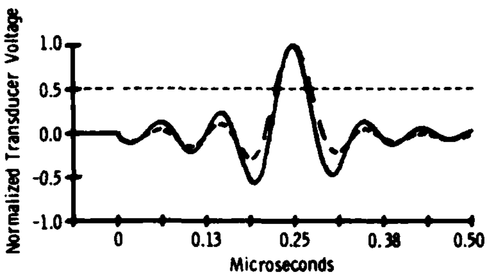

Figure 14. Superposition of the special pulse of Figure 7 (dotted curve) and the pulse obtained after attenuation proportional to the inverse of the frequency in megahertz (trace with the shorter duration of the larger cycle).

Table 2. CORRELATION BETWEEN TIME-DOMAIN PULSE WIDTH AND ATTENUATION FUNCTION

Half-Width of Major Portion of Pulse in Microseconds	Attenuated Spectral Amplitude Proportional to
0.039	f
0.047	1 (unattenuated signal)
0.055	$1/\sqrt{f}$
0.070	1/f
0.125	$1/f^2$

Table 3. EXPONENT x OF FREQUENCY DEPENDENCE AS A FUNCTION OF PULSE HALF-WIDTH w

x	w (from plot)	w (from equation)
1	0.039	0.039
0	0.047	0.047
-0.5	0.055	0.057
-1	0.070	0.071
-2	0.125	0.111

CONCLUSIONS

This investigation has produced two major results. It has demonstrated the feasibility of forming a special pulsed signal with a limited uniform spectrum of higher energy than contained in the equivalent spectral range of a sufficiently short rectangular d.c. pulse. It has further shown that a time-domain analysis of this special broadband pulse can be substituted for the more involved spectral analysis to distinguish among various types of signal attenuation processes. Thus, the method of ultrasonic pulse shape analysis can be used in place of ultrasonic spectroscopy to determine the microstructure of materials.[3,4] An added advantage of the time-domain analysis method is the retention of the phase information of the signal. Hence, should a test specimen exhibit a frequency dispersion of the ultrasonic propagation velocity, that important factor would not be missed.

An extensive listing of 44 literature references pertaining to the subject of ultrasonic spectroscopy is contained in Reference 5.

3. GERICKE, O. R. *Ultrasonic Spectroscopy of Steel.* Materials Research and Standards, v. 5, no. 1, January 1965, p. 23-30; also Army Materials and Mechanics Research Center, AMRA TR 64-44, December 1964.
4. GERICKE, O. R. *Ultrasonic Spectroscopy, Research Techniques* in Nondestructive Testing, R. S. Sharpe, ed., Academic Press, London, 1970, p. 31-61.
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